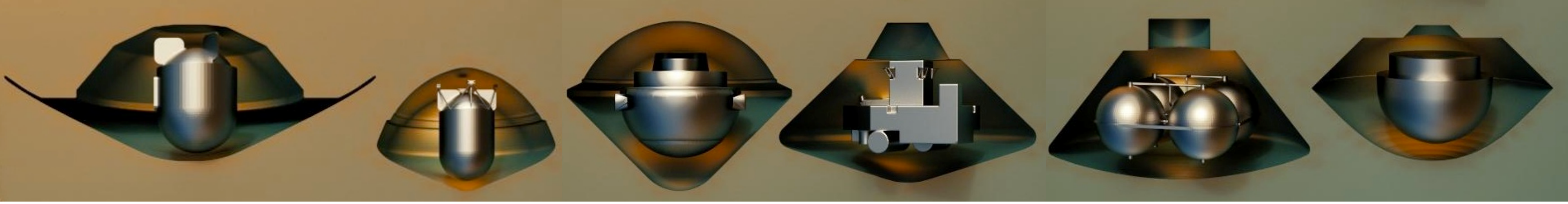
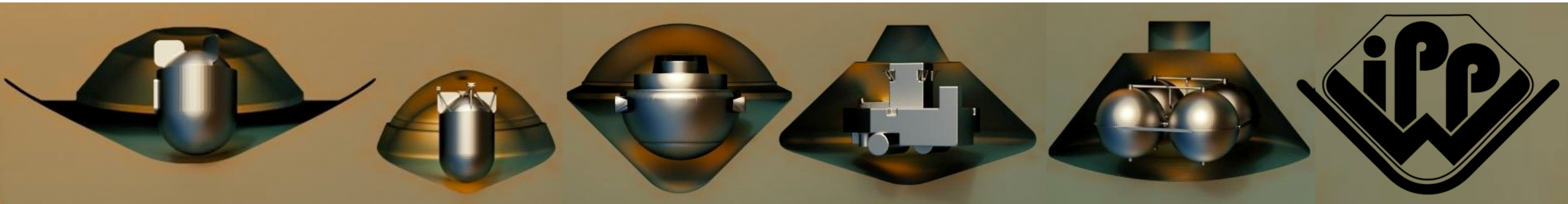


Entry, Descent, and Landing Systems Short Course

Subject: **Modern Advances in Ablative TPS**
Author: Ethiraj Venkatapathy
NASA Ames Research Center

sponsored by
International Planetary Probe Workshop 10
June 15-16, 2013
San Jose, California



Outline

- Physics of Hypersonic Flow and TPS Considerations
- Destinations, Missions and Requirements
- State of the Art Thermal Protection Systems Capabilities
- Modern Advances in Ablative TPS
  - Entry Systems Concepts
  - Flexible TPS for Hypersonic Inflatable Aerodynamic Decelerators
  - Conformal TPS for Rigid Aeroshell
  - 3-D Woven TPS for Extreme Entry Environment
  - Multi-functional Carbon Fabric for Mechanically Deployable
- Concluding Remarks

Considerations: Mission and Destination

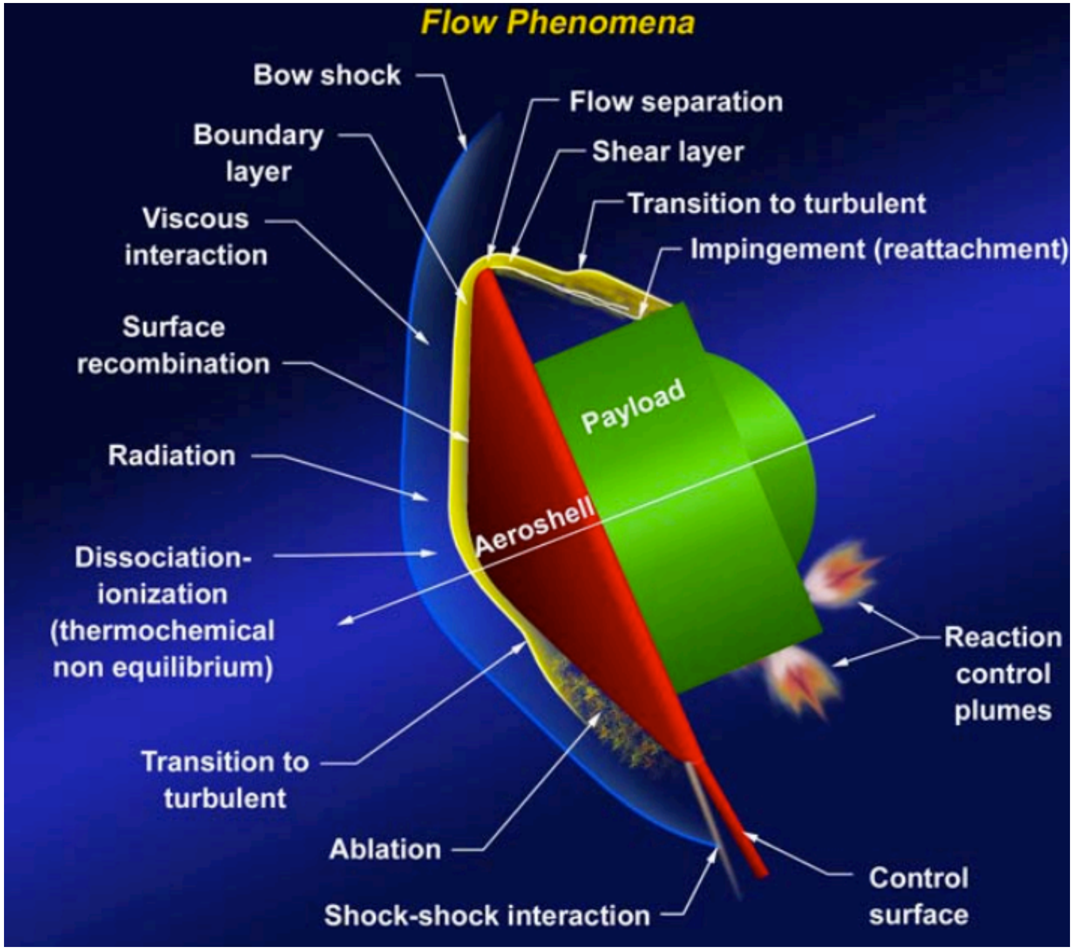
Destination (Entry Velocity)

- Earth Return from
  - Low Earth Orbit
  - Moon
  - Asteroids/Comets
  - Mars
  - Outer Planet Moons
- Mars:
- Venus
  - Orbiter with Aerocapture
  - Balloon and Landers
- Outer Planets
  - Jupiter (Galileo)
  - Saturn Probes
  - Neptune Orbiter and/or Probes
  - Uranus Orbiter and/or Probes
- Outer Planet Moons

TPS is a single string failure system

- Human vs Robotic
  - Human missions demand inherent robustness not required for robotic science
- Single, Dual and Multiple Entry Heating
  - Direct Entry: Ballistic vs Lifting
    - Ballistic is shorter heat pulse and relatively higher peak conditions (heat flux and pressure)
    - Lifting entries are longer pulse (higher heat load) and relatively lower conditions
  - Aerocapture
    - Entry conditions and benefit depend on the destination
    - Longer heat load than direct entry
  - Aerocapture followed by entry
    - Requires multi-use TPS

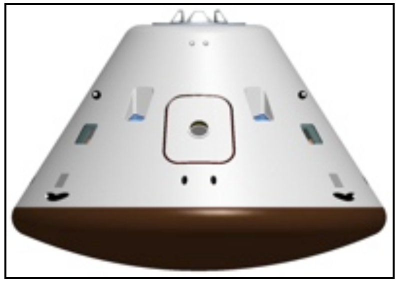
The Physics of High-Speed Entry and the Need for Thermal Protection



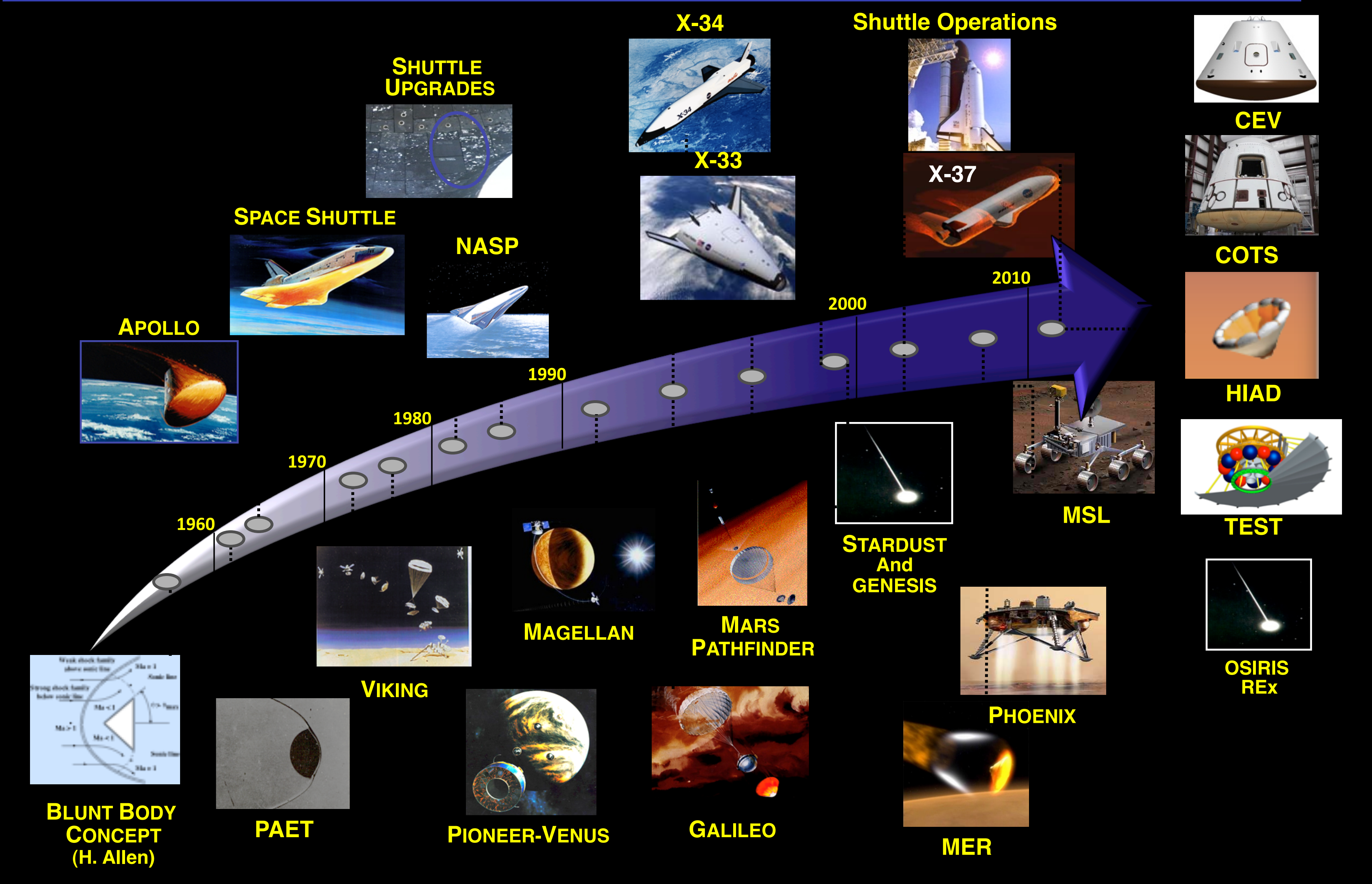
SPACE SHUTTLE

APOLLO

CEV

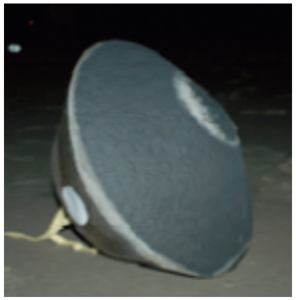


NASA Entry Systems: Past, Present and Future

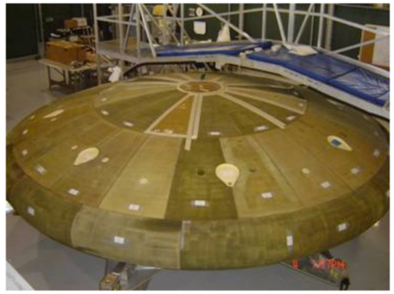


State-of-the-Art Ablative TPS and Limitations

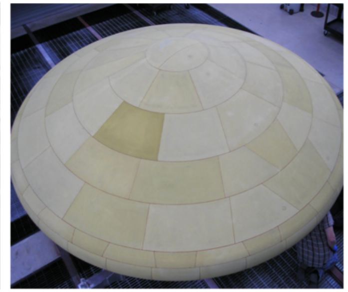
Stardust



Orion MDU



MSL



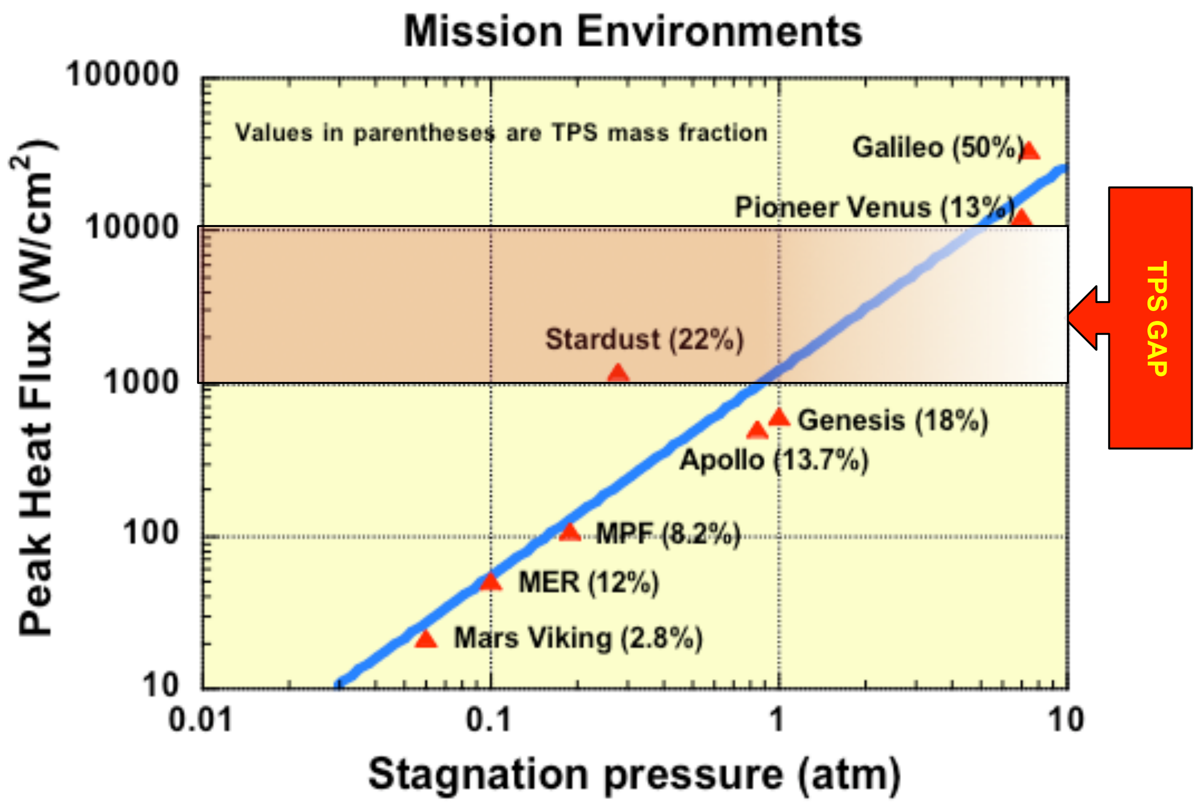
Dragon C1

SLA Failure Mode

TPS, once developed and flown, will be the first choice

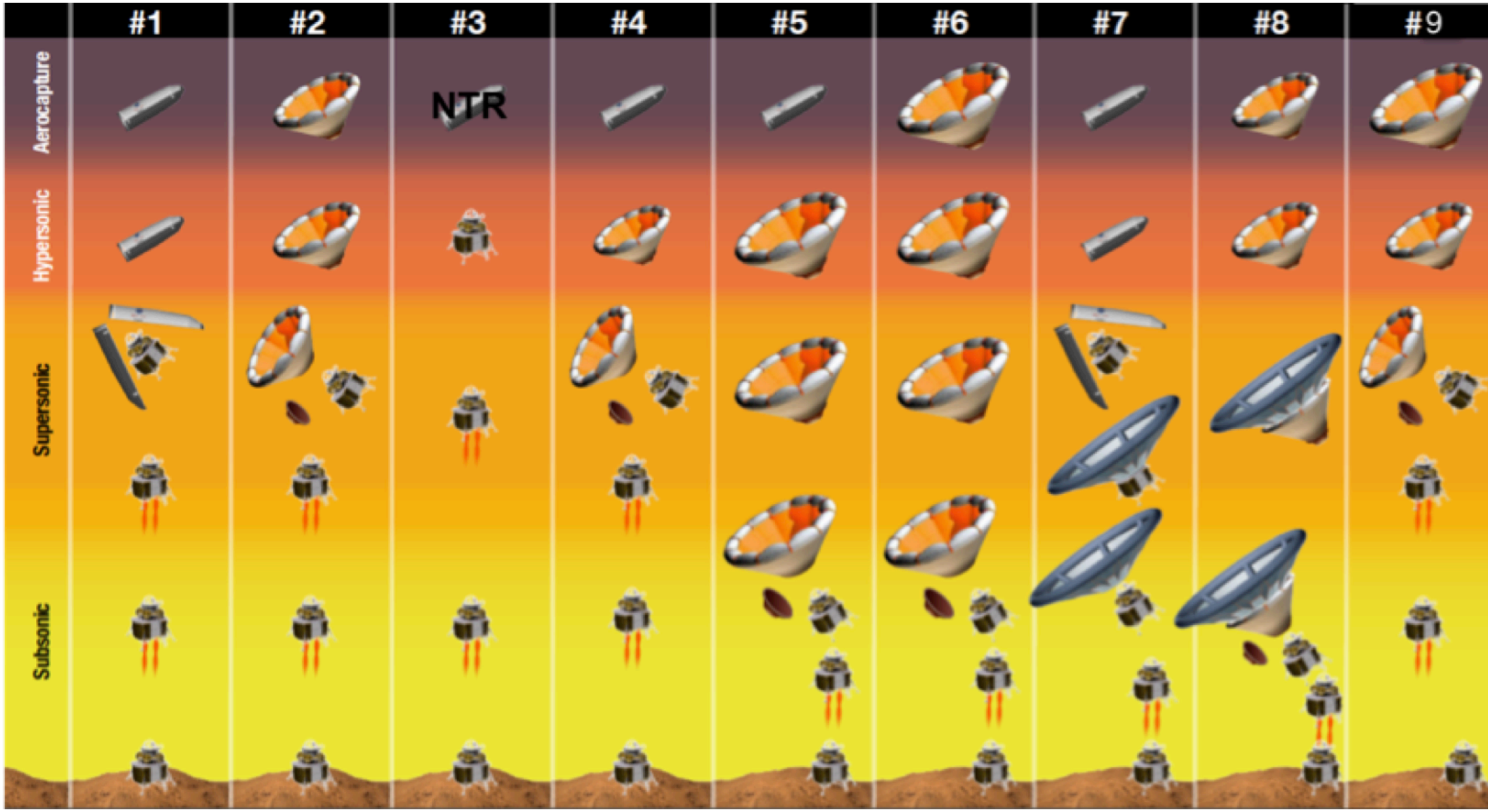
- Extrapolation to conditions not tested carried risk
  - SLA was the TPS of choice through CDR and the failure mode established during arc jet testing. Tiled PICA saved the day.
- Heritage argument and mission assurance are not synonymous
- Limitations in manufacturing and integration may add both risk and cost
  - Honeycomb systems – labor intensive
  - Curing time limitations;
  - Defects unavoidable due to humans in the loop
    - Super Light-weight Ablator (SLA) used on all Mars missions (except MSL)
    - Avcoat, the Apollo heat shield material (Choice for Orion)
  - Integration challenges

Ablative TPS Gap for Extreme Entry Environment



- Heritage Carbon Phenolic (CP)– Robust but not available
- PICA enabled Stardust and MSL. Avcoat enabled Apollo (and Orion)
- PICA and Avcoat are not capable of replacing heritage CP

Grand Challenge : Mars Human Missions Architectures under Consideration



Need: Ablators capable of and efficient to handle dual pulse for both rigid and flexible architectures.

FLEXIBLE TPS FOR HYPERSONIC INFLATABLE AERODYNAMIC DECELERATOR

- Physics of Hypersonic Flow and TPS Considerations
- Destinations, Missions and Requirements
- State of the Art Thermal Protection Systems Capabilities
- Modern Advances in Ablative TPS
  - Flexible TPS for Hypersonic Inflatable Aerodynamic Decelerators
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- Concluding Remarks

Flexible TPS for Hypersonic Inflatable Aerodynamic Decelerator

Flexible Thermal Protection System Development for Hypersonic Inflatabl Aerodynamic Decelerators

9th International Planetary Probe Workshop

16-22 June 2012, Toulouse

Joseph A. Del Corso, Walter E. Bruce III, Stephen J. Hughe
John A. Dec, Marc D. Rezin, Mary Ann B. Meador, Haiquan G
Douglas G. Fletcher, Anthony Calomino, F. McNeil Cheatwoc

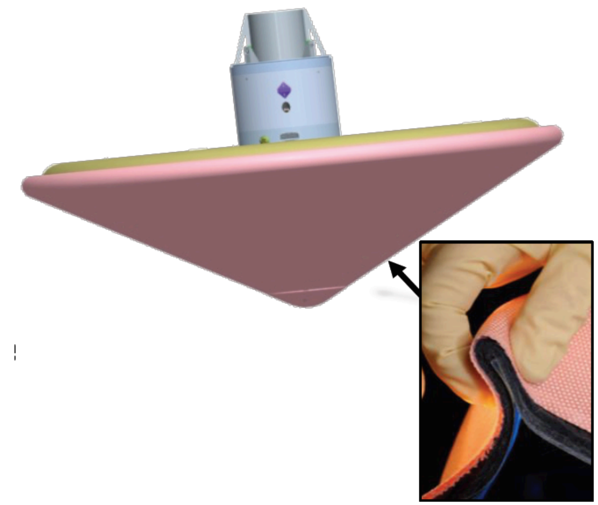
NASA Langley Research Center

Aerothermal Ground Testing of Flexible Thermal Protection Systems for ypersonic Inflatable Aerodynamic Decelerator

9th International Planetary Probe Workshop

16-22 June 2012, Toulouse

Walter E. Bruce III, Nathaniel J. Mesick, Paul G. Ferlemann,
Paul M. Siemers, Joseph A. Del Corso, Stephen J. Hughes,
Steven A. Tobin, and Matthew P. Kardell

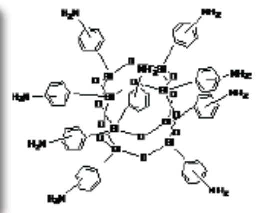


FTPS Requirements

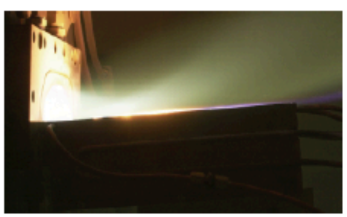
- Flexible (Foldable)
- Handle Rigors of Packing and Stowage
- Handle Aerothermal Loads
- Light Weight
- Compact to Small Volume

HIAD – Flexible TPS Integration and Potential Mission Applications

Flexible TPS Development and Qualification



$$\rho C_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) = 0$$



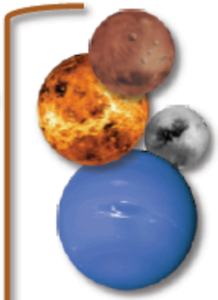
Sub-Orbital Flight Testing

Inflatable Re-entry Vehicle Experiments

System Demonstration

High-Energy Atmospheric Re-entry Test (HEART)

Future Missions



Robotic Missions

Crewed Earth Return

DoD Applications

Technology Development & Risk Reduction

2012 ***2013*** ***2015***

FTPS advances technologies supporting flight project needs

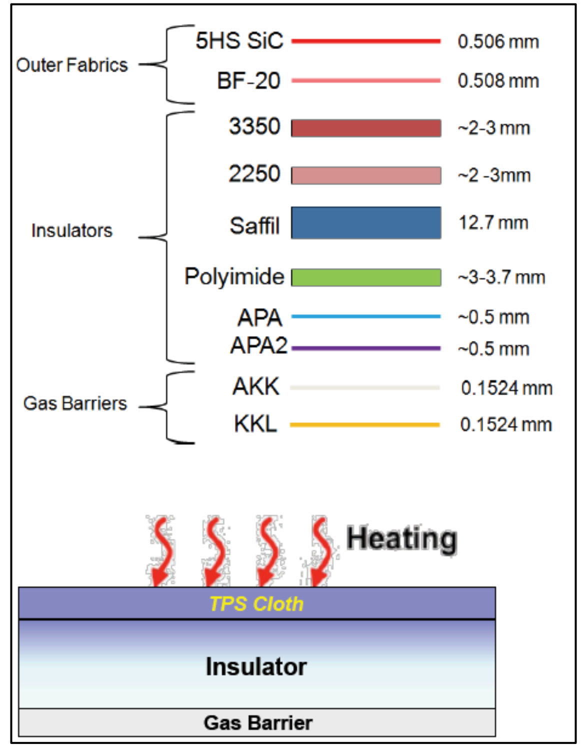
Flexible TPS Overview and Thermal Testing

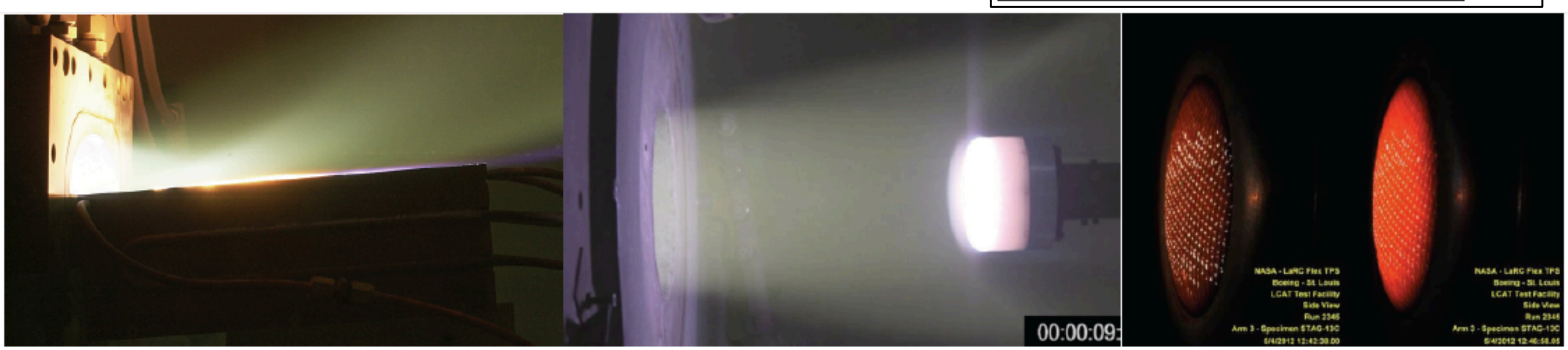
- **FTPS are designed to maintain structural component interface temperatures and survive reentry aero-thermal loads**
  - FTPS are designed to carry the entry mechanical and thermal loads

Flexible Thermal Protection Function

Heat Rate	Refractory Cloth
Heat Load	Insulator
Permeability	Gas Barrier

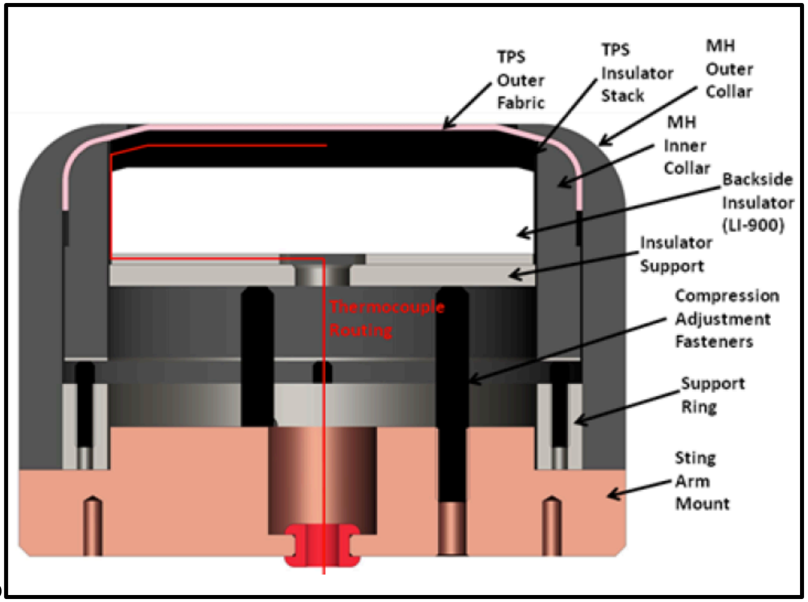
Modular design using functional layers

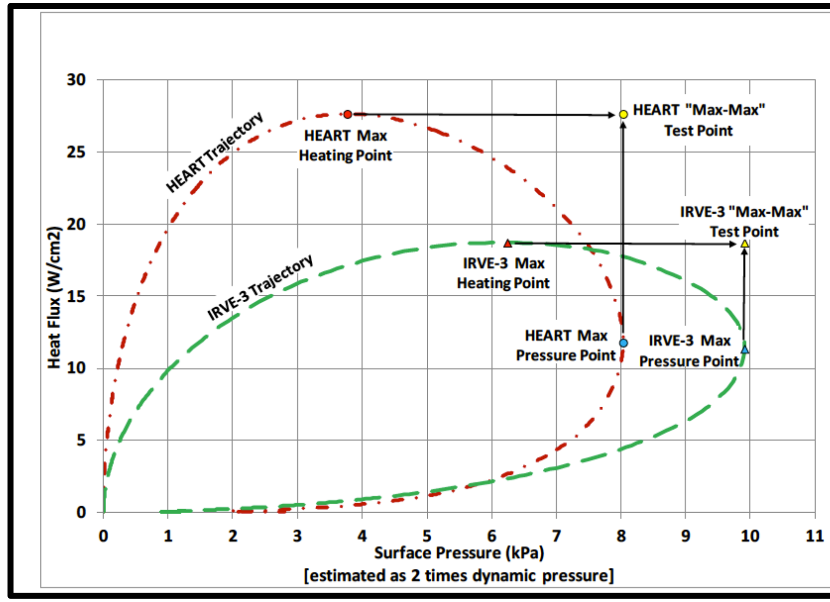




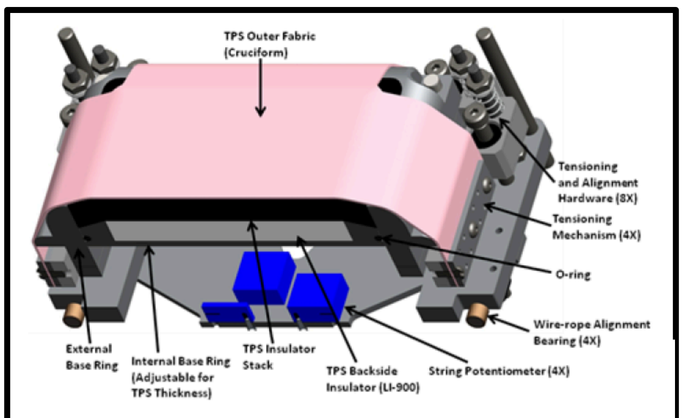
Combined Thermo-Structural Test Condition

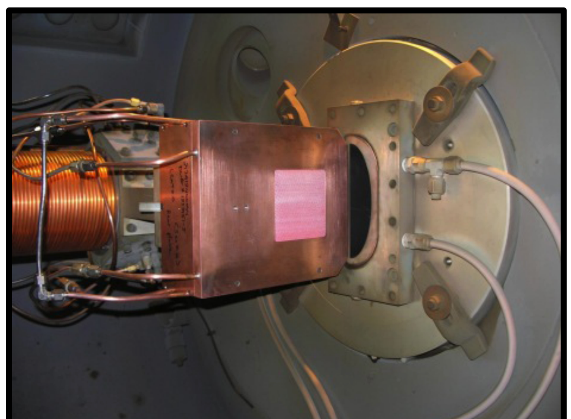
Stagnation Model Holder





Wedge Model Holder for Combined Thermo-structural Testing





Test Conditions	
Heat Flux (W/cm^2)	Surface Pressure (kPa)
20	3.1
30	4.8
40	6.6
50	4.0

Conformal Ablative TPS Development

- Physics of Hypersonic Flow and TPS Considerations
- Destinations, Missions and Requirements
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- Concluding Remarks

What is a Conformal Ablator

- Flexible ablators are conformal but conformal ablators need not be flexible. Conformal can be rigid.
- A conformal ablator, which is rigid, has a high strain-to-failure compared to conventional rigid ablators
- Conformal ablator by definition
  - Starts with flexible reinforcement (felt)
    - Allows for large geometry segments (broad goods)
    - Can be carbon or other suitable felt
  - Drape-able or formable during processing for easy integration
    - Conformable naturally provides lower thermal conductivity - in complex curved regions
  - Favorable/improved strain-to-failure
    - Eliminates need for strain isolation pads (direct bond to substrate)
    - Simplifies gore-to-gore geometries and allows gore-to-gore bonding (gap fillers eliminated)
    - Can accommodate CTE mismatch between structure and TPS

Rigid vs Conformal Ablator

Standard low density ablators: rigid substrate impregnated with resin and heated

➕ *impregnation*

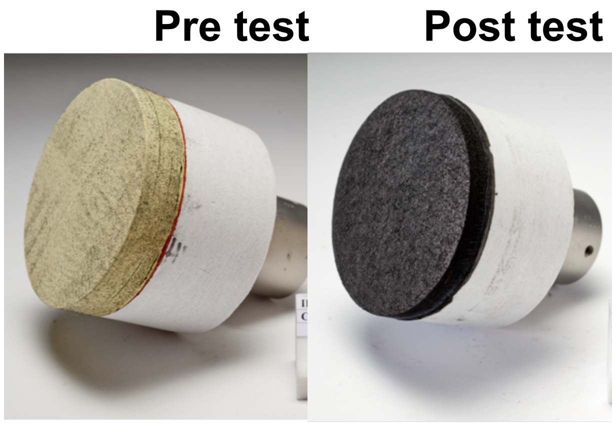
heat ⇨ *treatment*

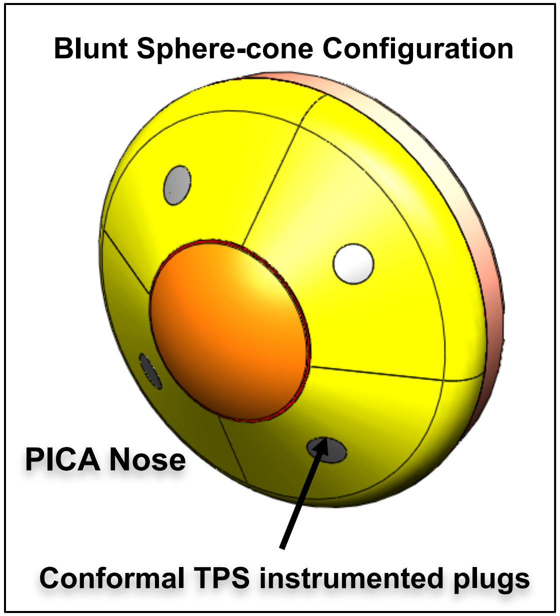
Example process for making Phenolic Impregnated Ceramic Ablator (PICA)

Conformal ablators start with a flexible reinforcement (Carbon or Silica)

Conformal Ablator Development

- Conformal 250 project goal was to develop an ablator with 250 w/cm^2 heat-flux, and pressure and shear levels similar to MSL PICA
  - began with 7 material variations
  - Started with ARMD conformal “recipe” as baseline
  - Varied felt type, resin loadings and additives
  - Plus included flexible PICA and Carbon felt/ silicone variants
  - IHF arc jet stagnation data
  - Limited strain-to-failure
- Two materials down-selected to carry further and test in more representative conditions
  - Carbon felt – Phenolic (C-PICA)
  - Carbon felt – Silicone (C-SICA)

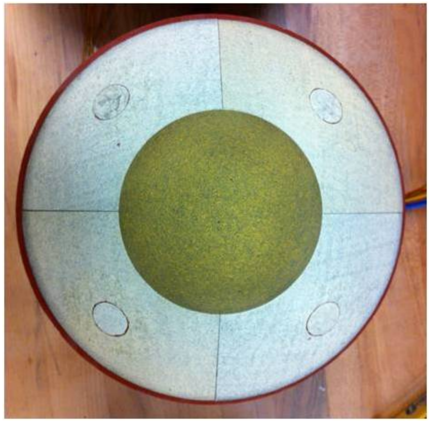




SPRITE 250

Arc jet and Structural Testing Results

Nose-tips lost during retraction of models



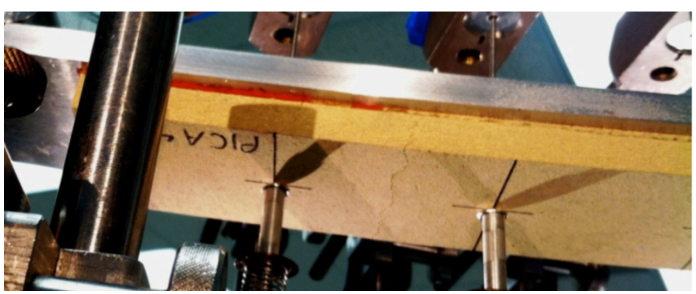
C-PICA

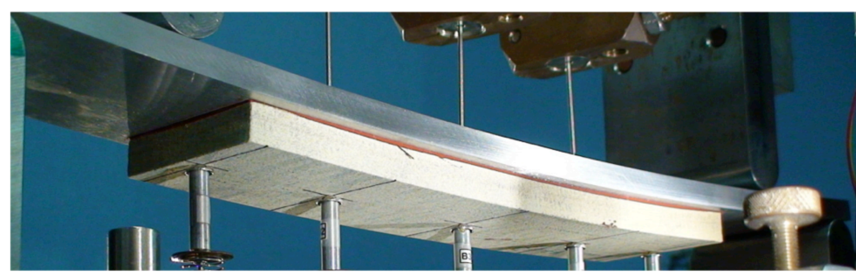
Flank heating: ~200 W/cm^2 60 sec ~400 W/cm^2 30 s

4-point bend tests:

PICA failure <750 lb, ROC ~145”

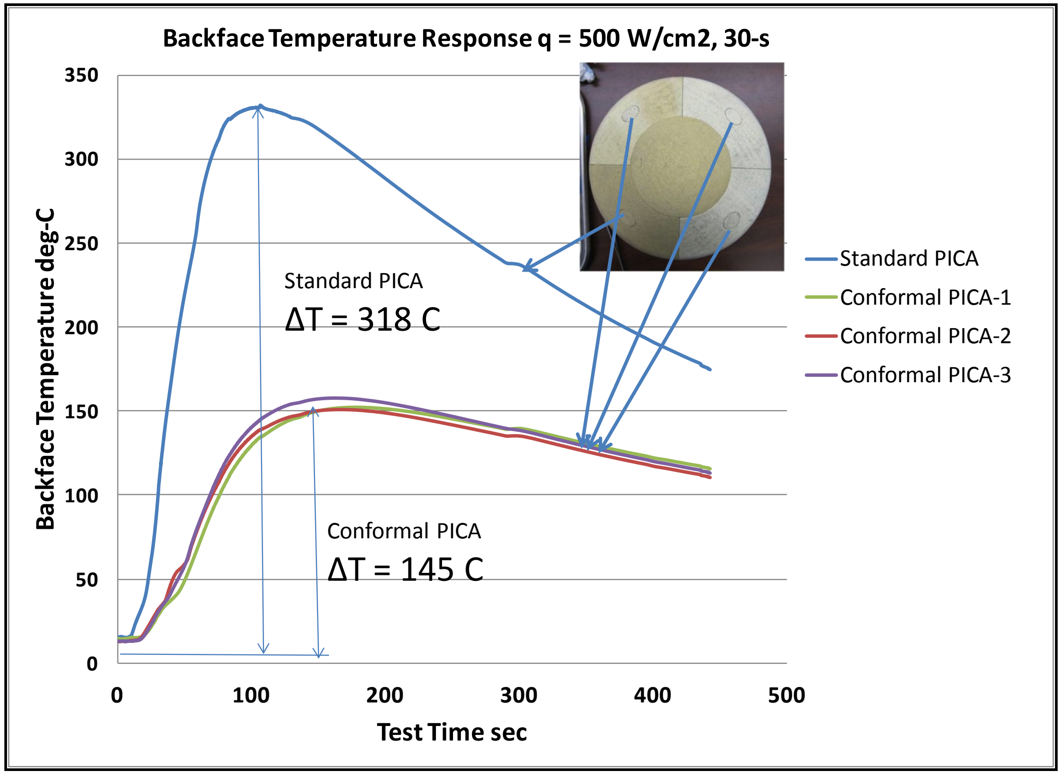
C-PICA no failure at 1500 lb, ROC <65”



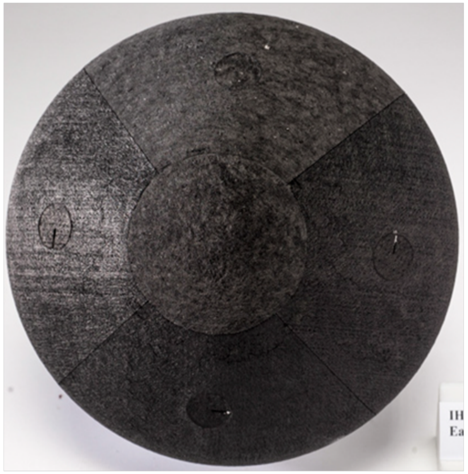


Conformal TPS Arcjet Testing for Thermal Response Model Development and Seam Designs Assessment

- Improvement over PICA
  - Recession comparable
  - Thermal penetration much lower

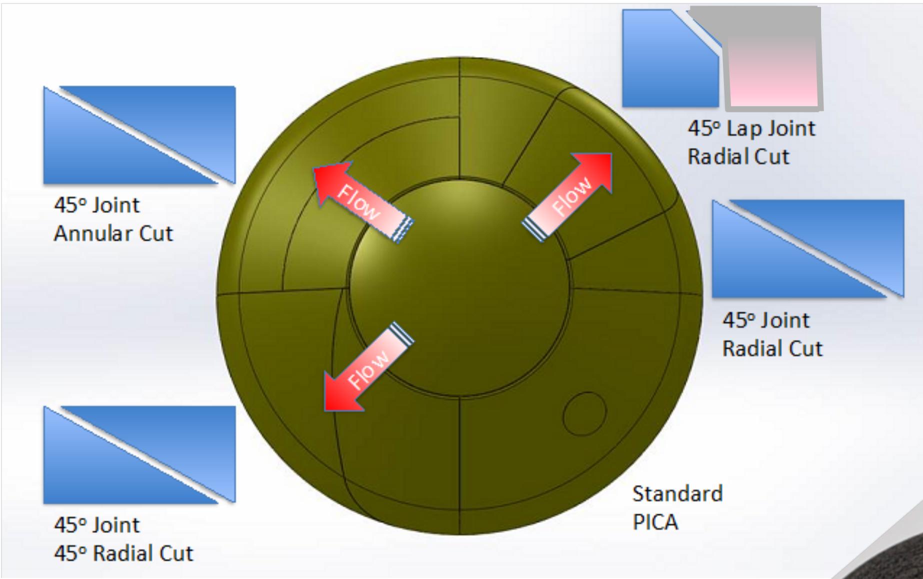


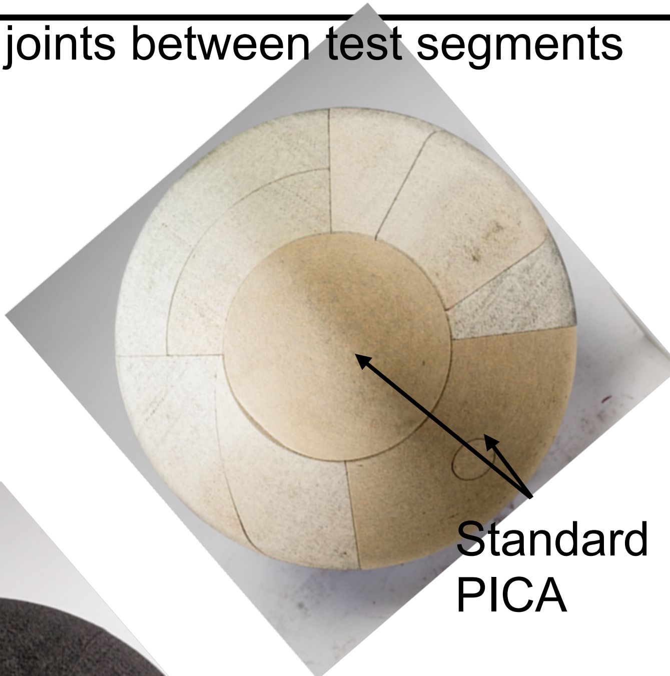
Flank heating ~500 W/cm^2, 30 s



Seam Design Evaluation

- All seams were well behaved, even 90° butt joints between test segments





- Flank heating
  - ~500 W/cm², 30 s

Arcjet Testing for Thermal Response Model Development and Seam Designs Assessment

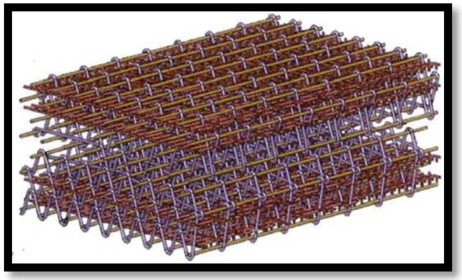
3-D Woven TPS for Extreme Entry Environment

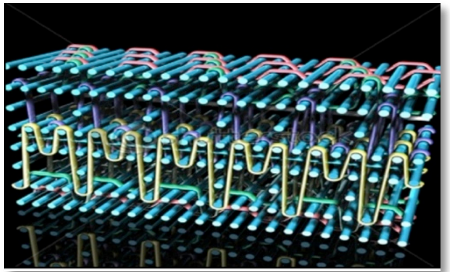
- Physics of Hypersonic Flow and TPS Considerations
- Destinations, Missions and Requirements
- State of the Art Thermal Protection Systems Capabilities
- Modern Advances in Ablative TPS
  - Flexible TPS for Hypersonic Inflatable Aerodynamic Decelerators
  - Conformal TPS for Rigid Aeroshell
  - **3-D Woven TPS for Extreme Entry Environment**
  - Multi-functional Carbon Fabric for Mechanically Deployable
- Concluding Remarks

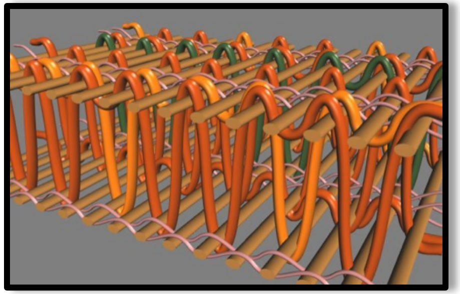
What is Woven TPS?

An approach to the design and manufacturing of* ablative *TPS by the combination of weaving precise placement of fibers in an optimized 3D woven manner and then resin transfer molding when needed

- Ability to design TPS for a specific mission
- Tailor material composition by weaving together different types of fibers and by exact placement using computer controlled, automated, 3-D weaving technology
- One-step process for making a mid density dry woven TPS
- Ability to infiltrate woven preforms with polymeric resins for highest density TPS to meet more demanding thermal requirements







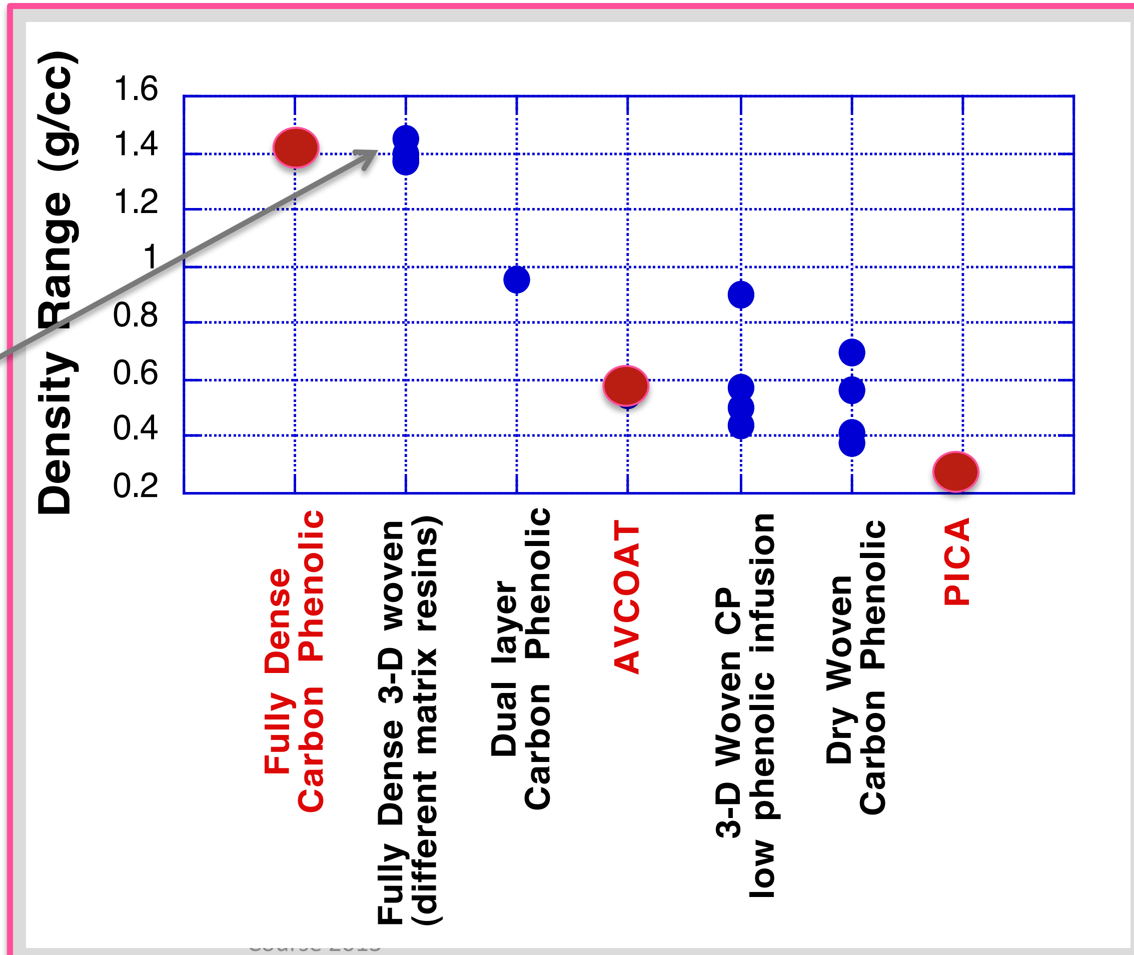
Woven TPS Project Goals:

- Develop and prove feasibility of woven TPS manufacturing technique
- Demonstrate via testing low, mid and high-density WTPS in order to fill the mid-density gap as well as finding a superior replacement for the heritage carbon phenolic

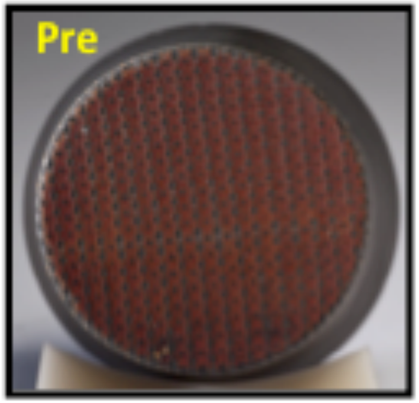
WTPS Accomplishments

- **Demonstrated the feasibility of manufacturing low, mid and high-density WTPS in order to fill the mid-density gap as well as a potential replacement for the highest density carbon phenolic**

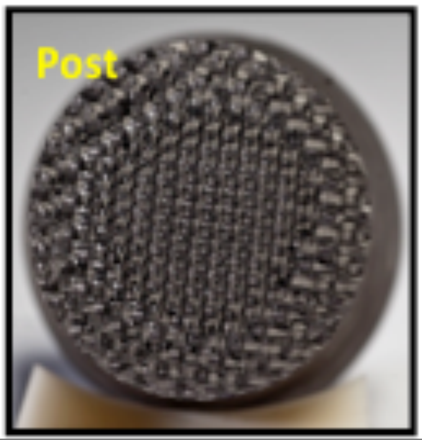
Fully Dense 3-D Woven (different resins)



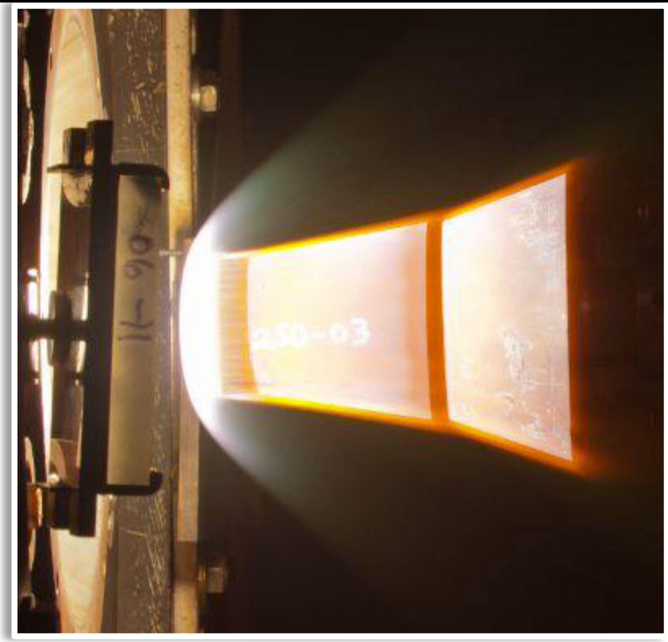
Successfully Arc Jet Tested Woven TPS in IHF and AEDC Arc Jet Facilities



Fully Dense
3-D WTPS



Mid Density
Dry Woven CP Blend



Stagnation testing evaluated:

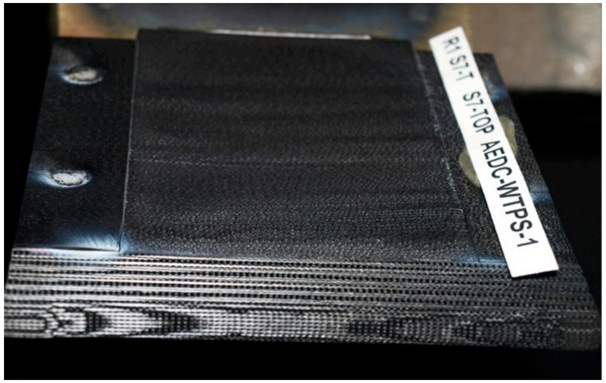
- 17 different Woven TPS, low-to-High density variants
- chop molded and tape wrapped carbon phenolic tested

Testing to date indicates high density 3-D WTPS materials have comparable performance in terms of recession as CP

Highlights from Wedge Testing: High Heat Flux, Shear and Pressure Conditions

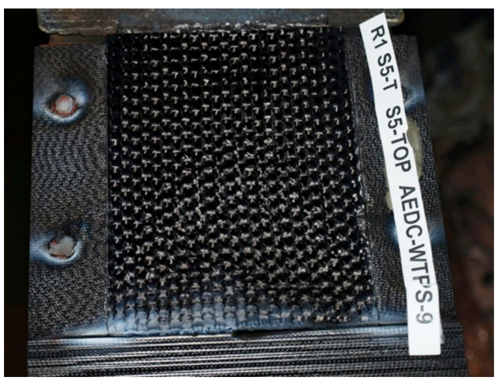
Traditional Carbon Phenolic

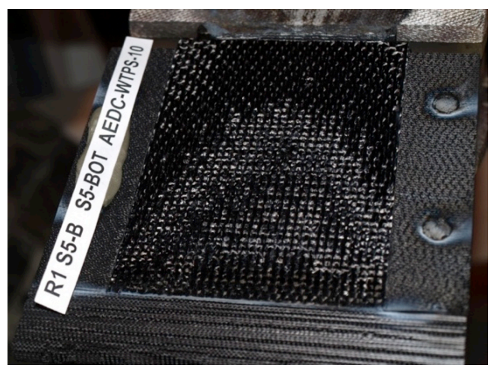
Shingled or (Tape Wrapped)

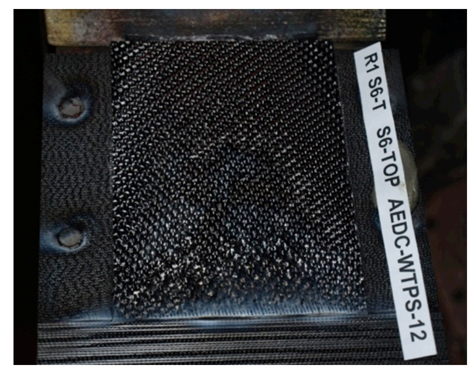


Chop Molded

3-D Woven TPS

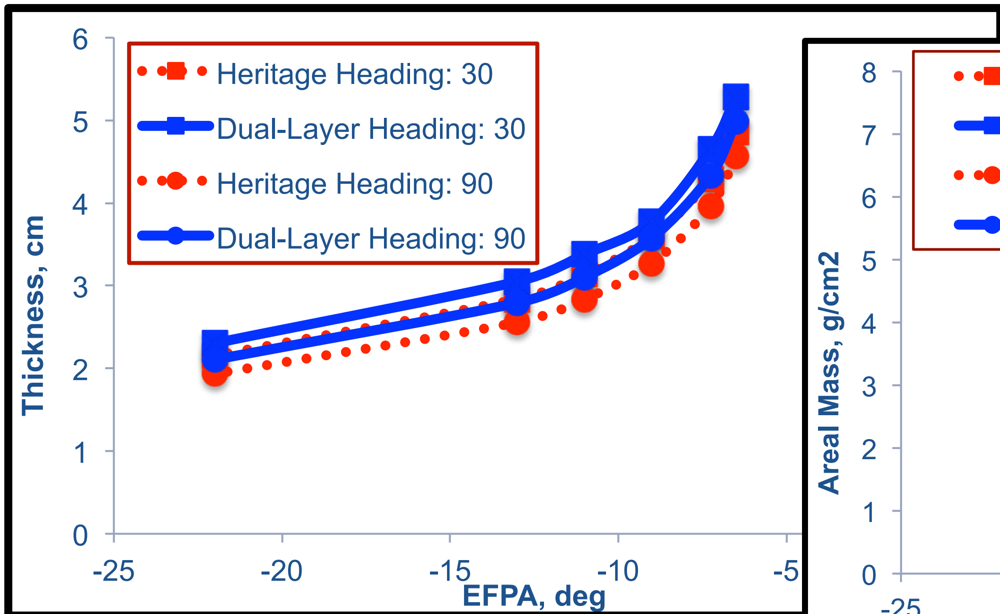


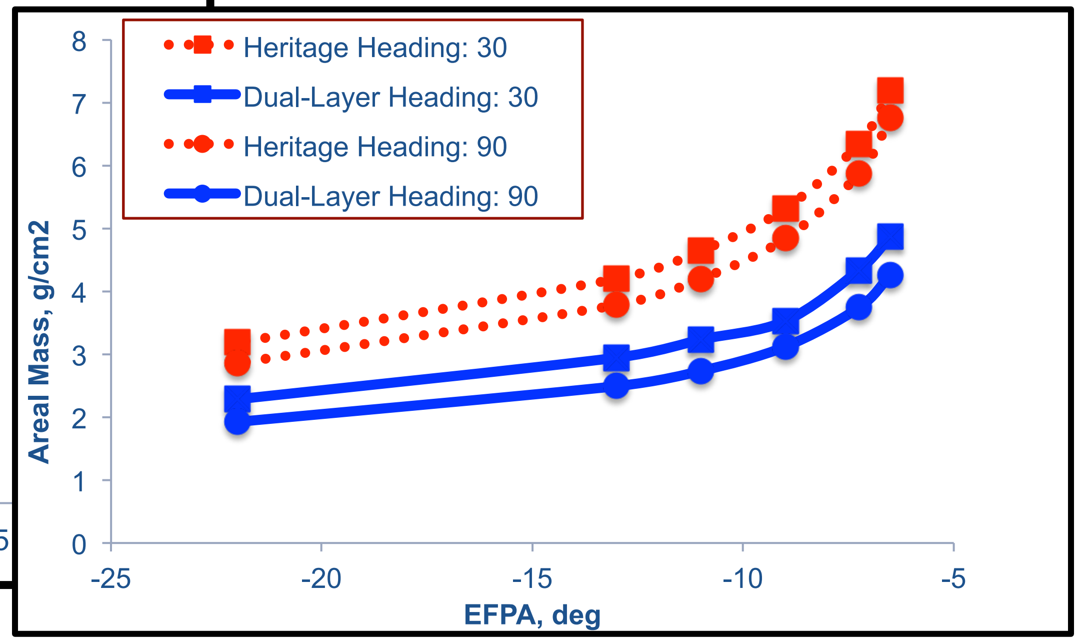




12 different Woven TPS, Mid-to-High density variants, along with chop molded and tape wrapped carbon phenolic were tested

Impact of WTPS on Saturn Probe Mission Design





Dual-Layer = WTPS; Heritage = CP

- **Heatshield mass using CP is ~40% of Entry Mass for a EFPA of -20 deg at 60 deg heading angle**

- **Minimal OML impact**: Zero-margin thickness estimate for carbon phenolic and WTPS is nearly identical for a wide range of entry conditions
- **Significant Mission Flexibility:** TPS mass savings of { 30% - 40%) over a wide range of entry conditions provide a significant mission architecture flexibility; Mission design, with WTPS, can trade risk of certification, mass or lower entry load

Carbon Cloth as Ablative TPS and Structure

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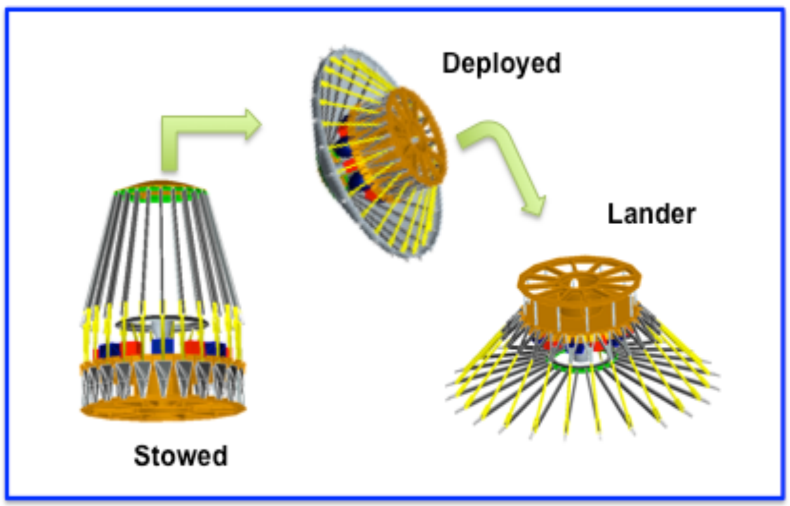
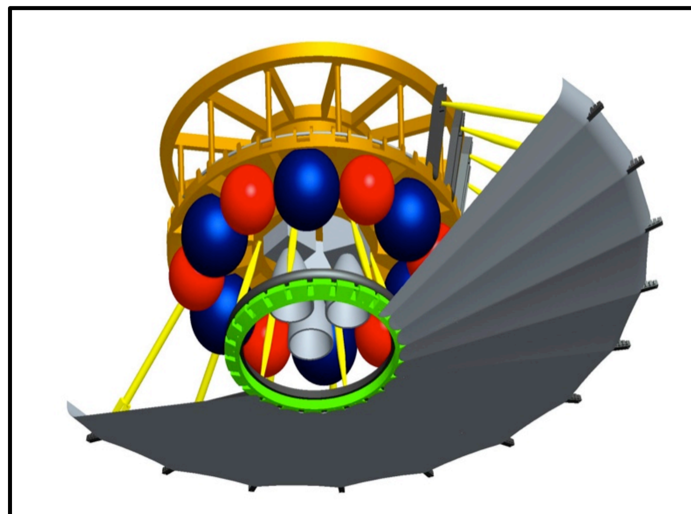
Adaptable, Deployable, Entry and Placement Technology (ADEPT) Concept for Human Mars Exploration

ADEPT can be scaled to deliver 40 MT payloads to the surface of Mars

- A rigid structural ring that reacts to the primary aerodynamic load and provides a simple interface to the delivered payload;
- A self-contained deployment system;
- Deployable “rigid” spokes for transmitting loads to the primary ring;
- Flexible thermal protection system (TPS) material;
- An ejectable nose heat shield for exposing the retro-propulsion system; and
- A primary gimbaled design for pivoting of the aeroshell and thereby enabling GN&C.
- A design that transforms the aeroshell into a lander configuration

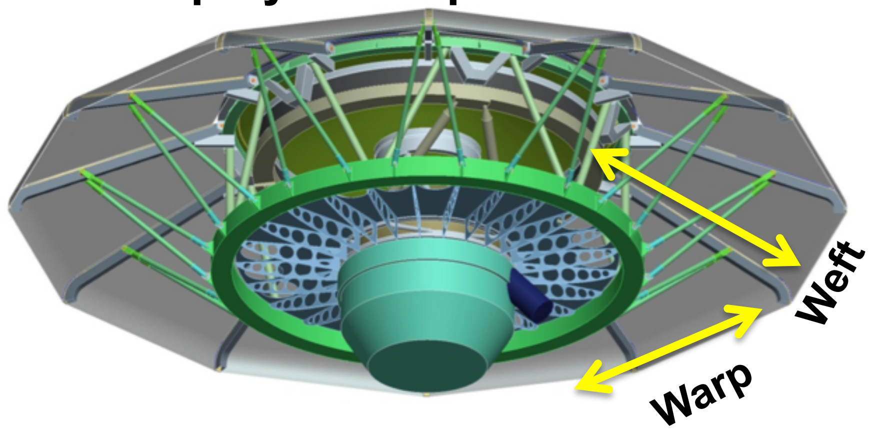


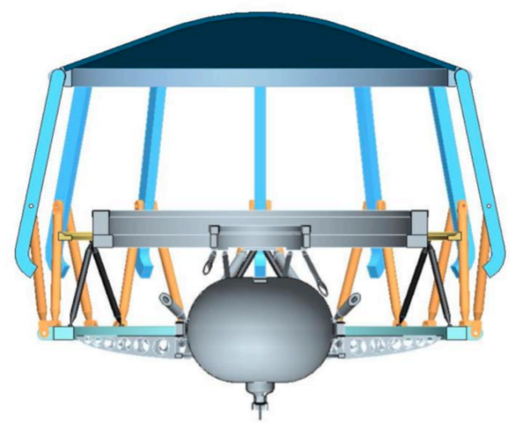


ADEPT-VITaL

- Adaptive Deployable Entry Placement Technology (ADEPT)-Venus Intrepid Tessera Lander[1].
- Blunt entry system with dry woven carbon, 0.15 inch thick "skin" and Advanced Carbon-Carbon "ribs".
- Low ballistic number and shallow entry flight angle gives ~10 X reduced deceleration and entry heating, enabling better science.
- Carbon fabric is taut, and must sustain combined entry heating and bi-axial mechanical loading.

Deployed in Space





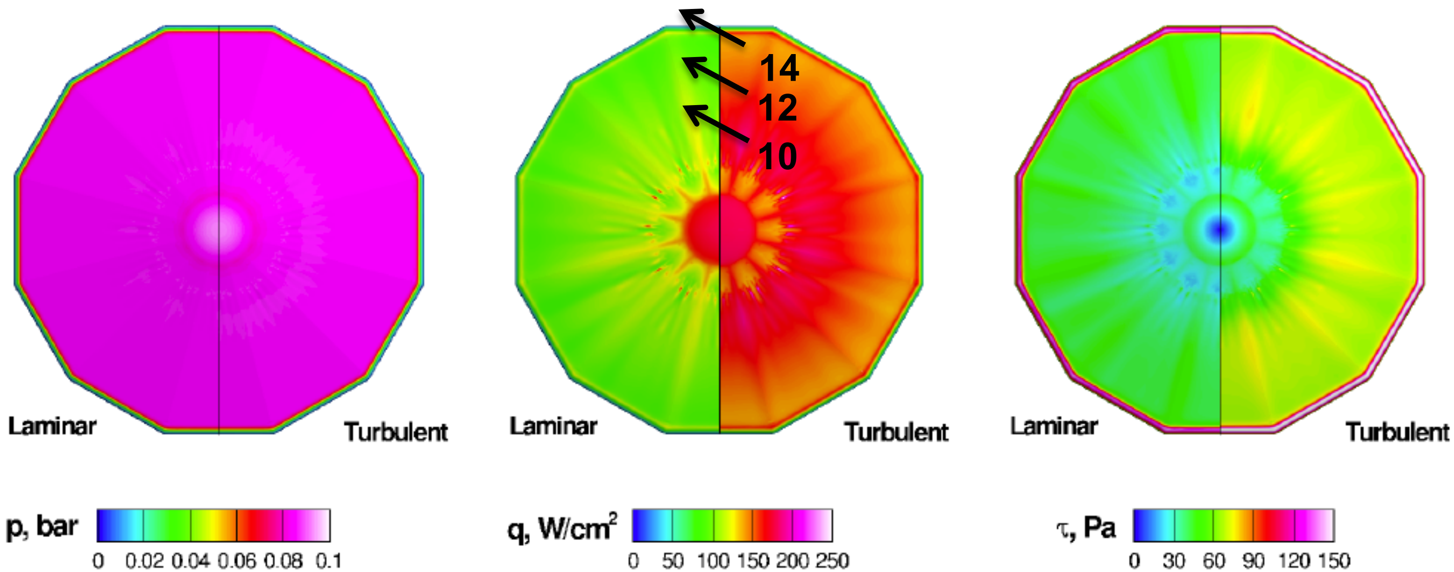
Stowed for Launch

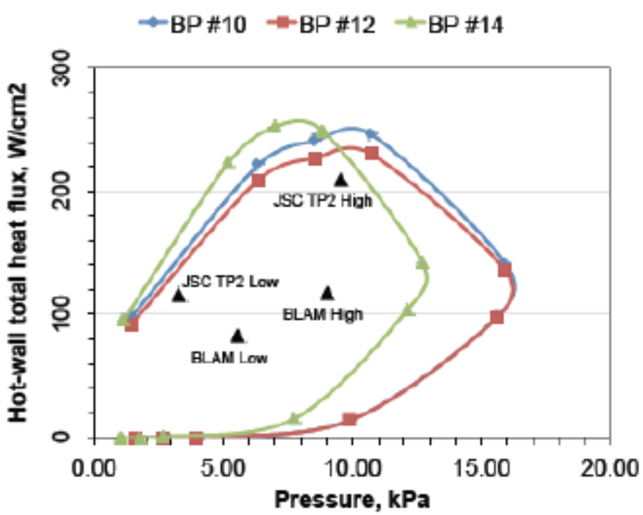
[1]Smith, B. Venkatapathy, E., Yount, B. Gage, P. Glaze, L. and Baker, C. *Venus in-Situ Explorer Mission Design Using a Mechanically Deployed Aerodynamic Decelerator* Big Sky IEEE Montana, March 2-9, 2013.

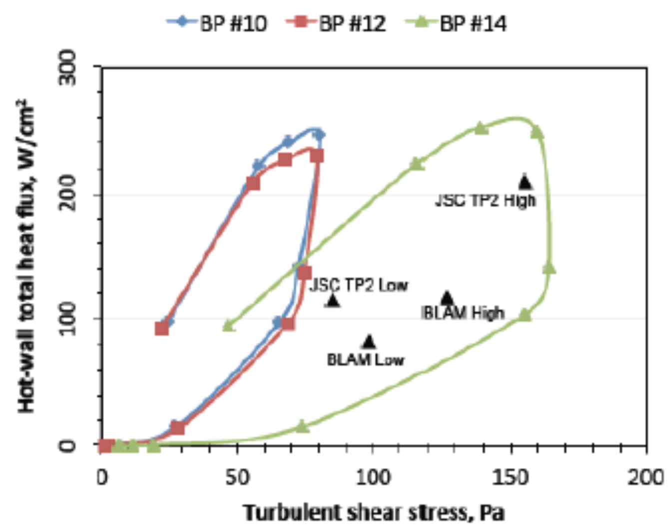
ADEPT-VITaL Aerothermodynamic Hot Wall Environment

(Head on Plots for Convective Component at Peak Heating – D.K Prabhu)

Total heating , Accounting for Radiation ~ 32 Percent Higher)_







Bi-axial Loaded Aero-thermodynamic Mechanical (BLAM) Test Objectives

1. Evaluate the capability of the weave to maintain structural integrity under combined, flight-like aerothermodynamic heating and bi-axial tensile loads.

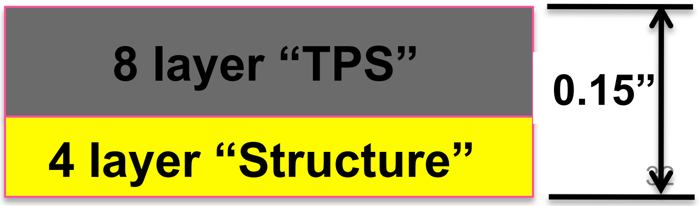
2. Evaluate the rate of layer loss as a function of different aerothermal and biaxial loadings.

Secondary: Provide arcjet tested fabrics to:

- Evaluate the residual load-bearing capacity of post-heated samples
- Examine the microstructure of arcjet tested fabric

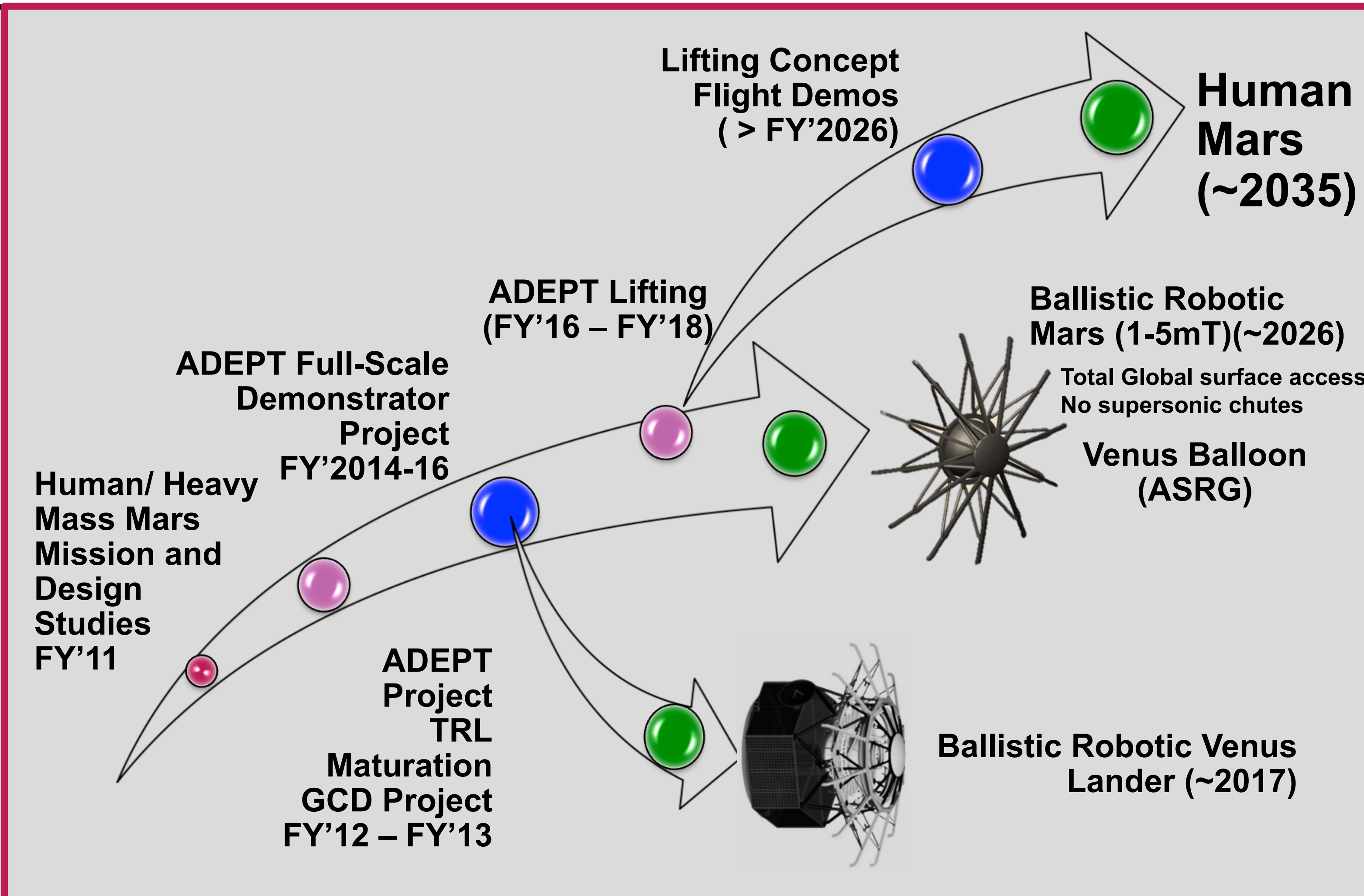
3 D Dry Woven Carbon Fabric that is specially designed to withstand the combined thermal and mechanical loads

[2]Arnold, J. O. et. al, *"Arcjet testing of Woven Carbon Cloth for Use on ADEPT"*, IPPW-10 San Jose State Univ. June 17-21,2013. *Manufactured by Bally Ribbon Mills.*



BLAM Movie Here

ADEPT Technology Maturation and Mission Infusion Timeline



ADEPT is an <u>Entry Architecture</u> that delivers for Game Changing Science and Exploration Missions in the Near, Mid, and Long term!

Summary

We started with

– State-of-the art thermal protection system, their limitations and the challenges ahead for future missions

Emerging TPS technologies

– Flexible TPS for inflatable or low ballistic coefficient entry systems

– Conformal ablative TPS for rigid or high ballistic coefficient entry systems

– 3-D Woven ablative TPS for extreme entry environment

– Flexible ablative TPS for mechanically deployable, low ballistic coefficient entry system

Each of the above emerging technologies have the potential to enable future missions and are game changers

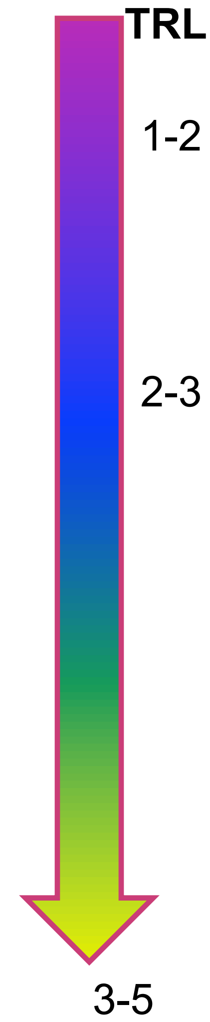
BACKUP

Need for Conformal Ablator

- Current NASA ablative heatshield materials require either high part count or extreme touch labor
- NASA has made some progress in light weight ablators like PICA flown on the recent Mars Science Laboratory, but that design required 123 tiles with complicated gap filler.
- Is conformal better? If so, in what way?
  - Material that isn't constrained to current manufacturing dimensions of 50x100 cm… but now can be made 150x100 cm or even larger – this significantly reduces part counts
  - Material that can deliver the same or better performance but with less weight where every pound saved can be added to more science
  - Material that is more compliant - this makes it more robust to loads and deflections and can save weight as well
  - Material that, because of it's compliance, can be directly bonded to an aeroshell and installed without gap filler – this saves integration time, cost and complexity

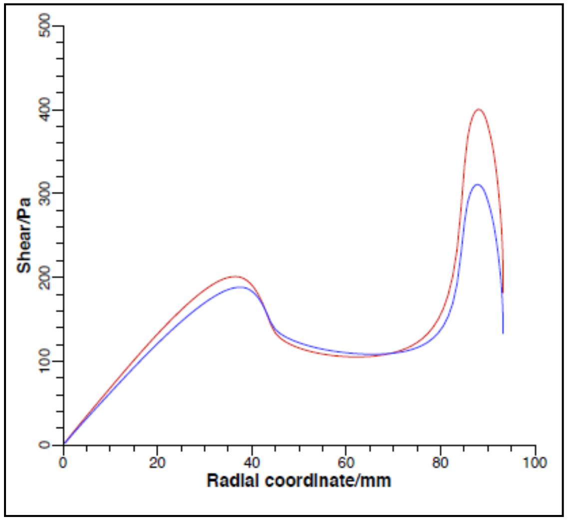
ARC Recent History of Conformal and Flexible Ablative Materials Development

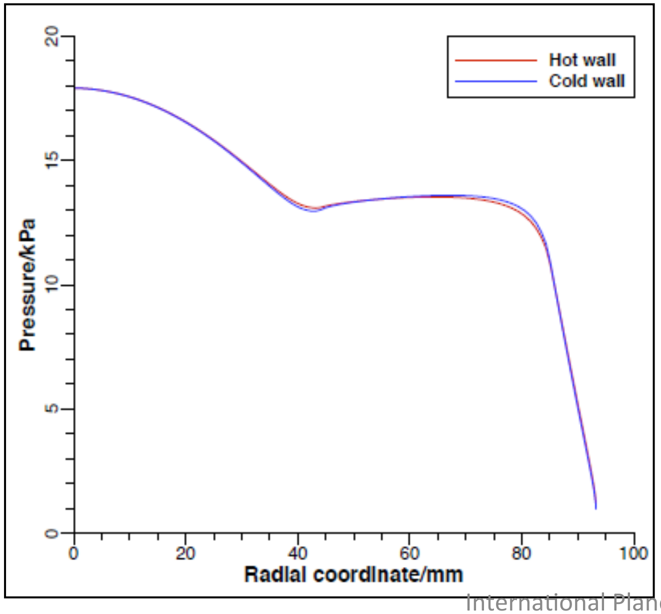
- 2007-2011 Funded by ARMD Fundamental Hypersonics to develop improvements to PICA in toughness
  - Initial research into baseline conformal PICA based on carbon felt with phenolic impregnation
- 2009-2011 Funded by ESMD Entry Descent and Landing Technology Development Project (EDL TDP) to develop flexible TPS
  - Developmental versions of several families of materials based on carbon, organic, and silica felts impregnated or mixed with phenolic or silicone resins
  - Results showed silica-based materials very capable $q<130\ W/cm^2$, carbon-based materials capable to at least $500\ W/cm^2$
- NOW: 2+ year project funded by Space Technology Mission Directorate Game Changing Division (STMD GCDP) to develop conformal ablators with the capability of at least $250\ W/cm^2$ and MSL-level shear

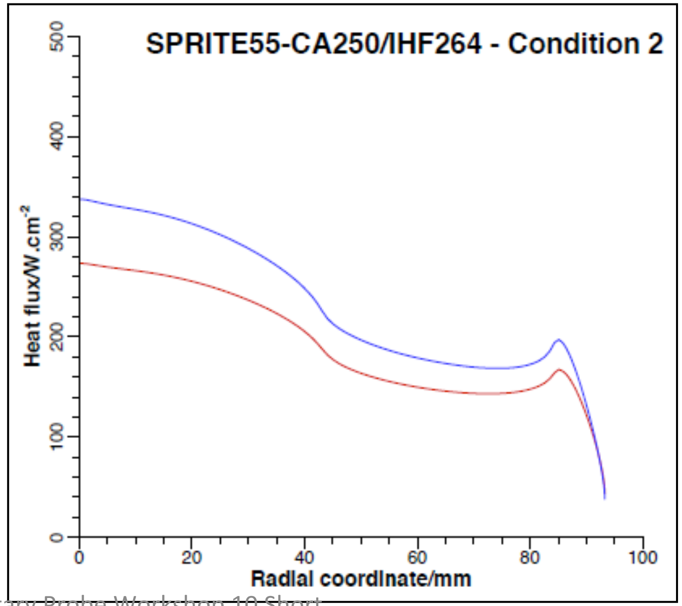


Small Probe (SPRITE 250) Arcjet Test Details

- Test conditions based on CFD of the flank section of a 55, 7.5” base diameter Small Probe (SPRITE) model
- Example: CFD plots for the 200 W/cm^2 test condition
  - Heat flux decreases slightly
  - Pressure and shear nearly constant on flank

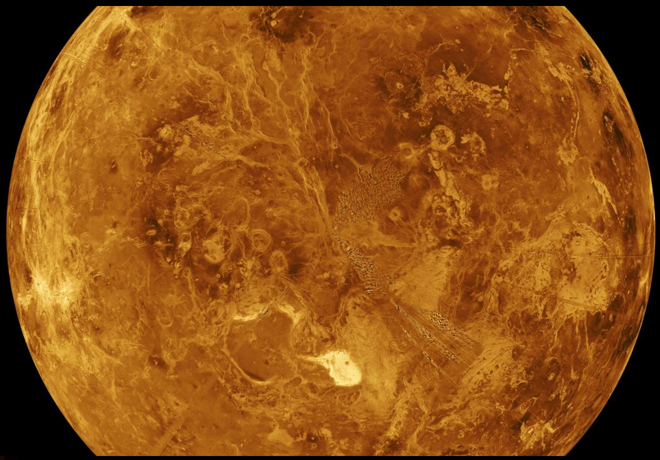






IPPW 10, June 17-21, 2013, San Jose, CA

Woven Thermal Protection System (WTPS) a Novel Approach to Meet NASA's Most Demanding Reentry Missions



Ronald Chinnapongse, Donald Ellerby, Margaret Stackpoole and Ethiraj Venkatapathy
NASA Ames Research Center

Adam Beerman, Jay Feldman, Keith Peterson and Dinesh Prahbu
ERC Inc.

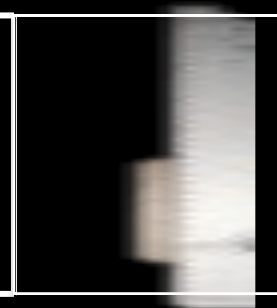
Robert Dillman and Michelle Munk
NASA Langley Research Center

Woven TPS Development and Missions

Woven TPS CIF
Idea Explored

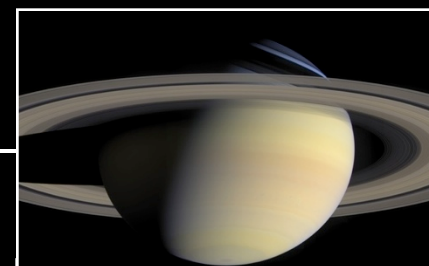
Woven TPS GCT BAA
(Competitively Selected)
Range of possibilities Explored

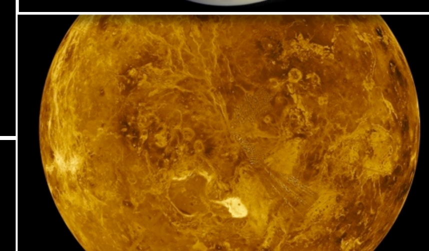
3-D Woven Multifunctional Ablative TPS (3D-MAT)
Enabling Orion and Providing a Material solution for Compression Pad (Lunar Return)



2017

Heatshield for Extreme Entry Environment Technology (HEEET)
Tech. Maturation to enable Venus and outer planets missions





2020 - 2022

April 2011
Jan. 2012
June, 2012
Oct., 2013